Cognitive Radio Network as Wireless Sensor Network (I): Architecture, Testbed, and Experiment

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Abstract—This paper explores the vision of a dual-use sensing/communication system based on Cognitive Radio Network (CRN). The motivation of the paper is to push the convergence of sensing and communication systems into a unified cognitive network. The concept design of this sensing/communication system is presented along with potential functions and challenges. A through tree target detection using real data collected by CRN testbed is demonstrated. The CRN testbed will be built based on Rice WARP nodes. To further exploit the advantages of dynamic spectrum access and frequency diversity, multi-frequency signal, which is similar to OFDM signal, are employed to for detection experiment in the harsh radio environment. The experiment results illustrate the vision of employing a CRN as wireless sensor network.

Index Terms—Cognitive radio networks, Wireless sensor network, Orthogonal frequency-division multiplexing (OFDM), Software defined radio (SDR)

I. INTRODUCTION

Cognitive Radio Network (CRN) has been widely investigated in recent years to increase the spectrum utilization in communications area. Meanwhile, the dual-use of radar/sensing and communications system is also exploited as in [1] [2], in which the radar/sensing system is embedded into communications system. This paper makes investigation on the convergence of the wireless sensor network and the communications system based on the cognitive radio network.

As OFDM signal is inherently fit with the cognitive radio system, the dual-use of the OFDM system and radar/sensing system has become an important research topic. This paper gives a review of the related literature. From the network perspective, the vision is presented to improve the combination of the wireless sensor network based on the cognitive radio network as backbone, including the implementation of the key features of CRN, adoption of creative and practicable theories, utilization of the Commercial Off-The-Shelf (COTS) communication components. Also, the possible challenges are discussed for future work. As the effort towards large scale wireless sensor network testbeds, the indoor through tree target detection experiment with single transmitter and receiver is performed to explore metrics used for target detection or localization. The experiment uses the MATLAB [3] as waveform design tool, the Rice WARP platform as the radio signal transmitter and receiver. Also, at the first stage of the experiment, the Digital Phosphor Oscilloscope (DPO) is used in the proposed experiment architecture for rough analysis of receiving signal. The multi-frequency waveform with some subcarriers suppressed, similar to None-Contiguous OFDM (NC-OFDM), is used as sensing signal. The receiving signal energy variation according to target position is observed in the testing. The result of the experiment gives valuable evidence for the vision of the amplitude based wireless sensing network. Finally, this paper proposes the future experiment architecture of wireless sensor network based on multiple WARP nodes, and the idea of cloud computing is also integrated.

The organization of this paper is as follows. The section II is the literature review. The section III is the description on the vision, challenge of the cognitive radio network as wireless sensor network. The section IV is the detail of the experiment. The section V gives the conclusion and also the discussion on the future work.

II. LITERATURE REVIEW

Multi-functional Software Defined Radio (SDR) for both radar and communication has become a hot research topic recently [1] [2] [4] [5]. OFDM system and OFDM waveform are explored. OFDM is the core technology in the wideband communication. OFDM is adopted by 3GPP Long Term Evolution (LTE), Wireless LAN (WLAN), Power Line Com-
munication (PLC), cognitive radio [6], as well as Asymmetric Digital Subscriber Line (ADSL) and Very-high-birate DSL (VDSL). OFDM waveform has also been used in the radar society [7] [8] [9] [10]. The key feature of OFDM waveform is multiple frequencies can be exploited simultaneously and in an orthogonal way. Meanwhile, the radio resources of all frequencies in OFDM waveform can be adjusted dynamically. The advantages of using OFDM in radar have also been summarized in [11]. Digital generation, inexpensive implementation, pulse-to-pulse shape variation, interference mitigation, noise-like waveform for Low Probability of Intercept/Detection (LPI/LPD), and so on are the benefits of OFDM waveform.

Similarly, the research about the joint OFDM-based radar and communication system has been carried out in Karlsruhe Institute of Technology, Germany [12] [13] [14] [15] [16], especially for the future intelligent transportation systems. Range estimation, angle estimation, and Doppler estimation are extensively studied. Besides, a communication waveform is proposed for radar in [17]. OFDM waveform can be used to solve the unambiguous radial speed in a single transmission and improve the signal-to-background contrast [17].

In telecommunications, Direct-Sequence Spread Spectrum (DSSS) is a modulation technique. Radar-Communication Integration based on DSSS has been discussed in [18]. A multi-functional RF system that integrates radar and communication can avoid mutual interference by using different Pseudo Random (PN) codes [18]. Direct sequence UWB signals are also applied [19] [20]. Oppermann sequences are utilized to generate the weighted pulse trains for the integrated radar and communication system [21]. Ambiguity function of weighted pulse trains with Oppermann sequences is analyzed. Oppermann sequences can facilitate both radar application and multiple-access communication.

Communication information can be embedded in the radar system through waveform diversity [22] [23]. Meanwhile, in the radar network, the communication message for instance the reports on the detected targets can be embedded into the OFDM radar waveform [24]. A unique covert opportunistic spectrum access solution to enable the coexistence of OFDM based data communication with UWB noise radar is presented in [25]. A multi-functional waveform has been designed, by embedding an OFDM signal within a spectrally notched UWB random noise waveform [25]. Besides, the performance of a cognitive WiMAX system in the presence of a S-band swept pulse radar is studied in [26]. WiMAX can still work with opportunistic transmission as long as it avoids interfering with the radar system [26].

III. COGNITIVE RADIO NETWORK AS WIRELESS SENSOR NETWORK

A. Vision

CRN and wireless sensor network have been widely studied separately. However, the our vision is to use CRN as wireless sensor network. In other words, we would like to embed wireless sensor network into CRN which acts as a backbone. Sensing and communication will be explored simultaneously. Because of network, sensing coverage and sensing performance will be improved. Because of cognition, machine learning can be applied for the high-level decision making. Meanwhile, dynamic spectrum access, the key feature of cognitive radio, will be used to make the smooth coexistence of sensing and communication.

CRN will be built based on the commercial communication components. Thus, our vision is also to push the capability of the communication components to the limit. The sensing task is performed using these communication components instead of the sophisticated equipments or the dedicated radar sets. Meanwhile, these communication components will be the programmable SDRs which are well suitable for building multi-function system at least including sensing, computation, and communication [27] [28]. Take wireless tomography [29] [30] as an example. Multiple Universal Software Radio Peripheral 2 (USRP2) will be used to set up a close-in wireless sensor network [31] the goal of which is to form the image of the target in the scene by wireless tomography.

Optimization theory, machine learning, real-time adaptive signal processing, and graph theory will be applied. An integrated sensing/communication cognitive network should have the capabilities of cognition, waveform diversity, network resource management, dynamic network topology, multi-level synchronization, and cyber security. In terms of wireless sensor network, the following functions should be supported: (1) interference mitigation; (2) detection and estimation; (3) classification, discrimination, and recognition; (4) tracking; (5) sensing and imaging.

B. Challenge

Though the vision is very promising, we still have to face the inevitable challenges before we touch the goal. Because of the commercial communication components, even with the capability of programmability, the transmitted power and the signal bandwidth are limited. Thus, CRN with a large amount of radio nodes is needed to compensate the sensing performance loss due to the limitation of power and bandwidth. Meanwhile, in order to improve sensing resolution, high-precise synchronization is a must. However, the accurate measurement of phase rotation and time delay needs advanced hardware, precise timing information, and real time signal processing, especially for the case the transceiver is not colocated. Thus, CRN should try its best to coordinate its radio nodes to carry out sensing task. Besides, spectrum, sometimes, is not available due to the usage of primary users. CRN should have a quick response to the dynamic working radio environment and distribute the sensing task based on working environment, work load, and performance requirement.

IV. EXPERIMENT

Our experiment is performed in the indoor environment, in which the real communications environment is investigated to find the impact on the sensing purpose. As described previously, usually the OFDM technology is used in cognitive
radio network for better frequency usage. Especially, when the primary user occupies part of the OFDM subcarriers, the secondary user has the capability to sense the frequency usage and selects the rest of the unused subcarriers to adopt the NC-OFDM signal as its radio transmission resource within the same OFDM bandwidth. In our experiment, it is assumed that the spectrum sensing has been done successfully before carrying out the target detection, which means the transmitter and receiver know which subcarriers are using. The experiment is focused on signal generation, transmission, and the analysis on the received data. Also, for simplicity without generality, the multi-frequency signal is used for testing, instead of the ideal OFDM signal. In the current stage, the single transmitter and receiver experiment is performed, aiming to explore the metric for target detection and localization in future large scale wireless sensor network.

Wireless open-Access Research Platform (WARP) [32] is exploited to construct CRN to realize the active monitoring of transmission and reception parameters. As a combination of FPGA based real-time processor and a multi-core host computer with a Graphic Processing Units (GPU) for acceleration, the CRN testbed is constructed by exploiting WARP to achieve cooperatively radio frequency spectrum, user behaviour and network state through the active monitoring of transmission or reception parameters in the external and internal radio environments.

Our current nodes of CRN testbed are developed based on WARP. WARP is a stand-alone hardware platform. The on-board computing resource comes from a Xilinx Virtex-4 FX100 Field Programmable Gate Array (FPGA) with PowerPC processors embedded in the FPGA. The WARP boards can be connected to the local network through standard interfaces, for instance, Gigabit Ethernet. The powerful computers in the local network run softwares like MATLAB, monitoring incoming traffic from the nodes, performing corresponding computing tasks, and sending results back to the nodes. From the point of view of the nodes, the computers are just like their hardware accelerators.

A. Setup

The experiment environment is setup as in Figure 1. Two horn directional antennas are used as radio wave transmitter and receiver respectively. Each antenna is connected with a WARP board and the two WARP boards are both communicating with the computer through Ethernet switch. The target used in this experiment is a metal plate which can reflect the radio wave well and it is placed behind trees to simulate the case that the target is hidden in forest. The distance between the antenna and the target is about 3 meters. The width of the area covered by trees is about 1.5 meters.

On the PC, the MATLAB code is developed to implement three functions: (1) The waveform design and generation for the multi-frequency signal. (2) Control and collaboration for the transmitter and receiver. (3) Post analysis for the received data.

On the WARP board, we are using the reference design provided by Rice University to transmit and receive the generated waveform. The WARP board as transmitter gets the waveform data from the MATLAB via ethernet interface with computer and delivers the data to radio board for radio transmission. The other WARP board as receiver collects the data from the receiving antenna and ships the data back to the MATLAB code for processing.

The detail experiment procedures for the collaboration between the WARP platform and the MATLAB are described in the following subsections.

B. Experiment Procedures and Results

For the purpose of verification, we split the experiment to two stages: 1) Use one WARP node as transmitter and the DPO as the processor of the receiving data. 2) Two WARP nodes are deployed as transmitter and receiver respectively.

a) One WARP node as transmitter and the DPO as receiver: This stage of experiment has two purposes: (1) Verify the spectrum of the generated multi-frequency signal. (2) Observe the impact of the target on the receiving signal intuitively. The experiment architecture is as Figure 2.

The experiment steps are described in steps as below:

1) Generate the desired radio waveform at the transmitter. Some MATLAB code from the WARP Lab reference design provided by Rice University is reused. Our goal is to generate baseband multi-frequency signal with part of the subcarriers suppressed. The bandwidth of the generated signal is 10MHz which contains 64 subcarriers.

2) The base band signal data is written by MATLAB to the memory of the WARP board through ethernet connection and then the data is transfered to the radio board with base band Digital-to-Analog Converter (DAC) and upconversion, finally transmitted via directional radio antenna. The base band DAC and Analog-to-Digital (ADC) of WARP board is working at 40 MHz sample rate.

3) The radio signal is captured by the receiving directional antenna and delivered to the DPO which collects 200
Fig. 3. Power spectrum density of the transmitting multi-frequency signal.

us of time series and also calculate the Power Spectrum Density (PSD) for this data.

As it is hard to collaborate the WARP transmitter and the receiver acted by DPO, the continuous multi-frequency signal is used in experiment to ensure the DPO can always capture the useful time series and get the available PSD.

At the transmitter, the PSD as Figure 3, in which part of the 64 subcarriers are suppressed and the bandwidth of the signal is 10MHz.

Two cases are tested for this stage of experiment.

1) There is no target within the detecting area. The corresponding PSD of the receiving signal is displayed at DPO as Figure 4.

2) Without changing any radio parameters in case 1, like the amplifier gain, transmitting signal attributes, etc., a metal plate target is just placed right on the direction of the transmitting antenna and with best angle to the receiving antenna. The corresponding PSD at the receiver is also displayed at DPO as Figure 5.

Intuitively, the most visible difference for the PSDs in the two cases are the change of the receiving energy. For case 1, the amplitudes at these allocated frequency point at receiver are within range of -78.5dBm to -74.6dBm, while for 2, the amplitudes are increased to the range of -74.5dBm to -72.1dBm, which means the reflectivity of the target does increase the the receiving energy. In the next stage of the experiment, the more detail test based on two WARP nodes is performed to explore the relationship between the position of the target and the receiving energy.

b) Two WARP nodes are deployed as transmitter and receiver respectively: This stage of experiment replaces the DPO with the other WARP board as the signal receiver. The experiment architecture is as the Figure 6.

The procedures of this stage of experiment are as follows:

1) Similar to the first stage of the experiment, the multi-frequency signal is generated by MATLAB, and the signal is still using 10MHz bandwidth of 64 subcarriers with part of the subcarriers suppressed, as shown in Figure 3. However, instead of continuous transmission, the signal
is only sent within a short time frame with the some zero value samples that are put into the front part and rear part of the whole time serie. So the signal has a start edge and stop edge, as the upper half of the Figure 7, in which the length of useful signal is 8192 samples. The zero value part of the signal acts as a protection which is to ensure that it can be observed at the receiver for whether the useful signal is wholly captured or not.

2) The signal data is downloaded to the memory of the WARP board. Just note, the length of the time sequence is the same as the memory size so as to no junk data is sent out.

3) Then MATLAB, via ethernet interface, sends command of transmitting start to the WARP transmitter, and the command of receiving start to the WARP receiver, to trigger the radio wave transmission and receiving. Due to the random delay of the ethernet frame and the running delay of the embedded software at both the WARP board, the actual time for the start of transmission and receiving of the signal can not be exactly the same. However, the delay between the transmission and receiving is very small. And because of the protection of zero value part sequence, it is observed that the useful signal with length of 8192 samples is captured as the lower half of Figure 7. It could also be observed that the delay between the transmission sequence and the receiving sequence is quite stable in statitisc, with value of around 2000 samples (50 us) by the variation of 2 to 3 samples (50 to 75 ns) for different tests. It should noted that this delay is mainly caused by the fact the WARP transmitter and receiver can not be triggered at exactly the same time in this experiment.

4) The WARP receiver transfers the received signal data to MATLAB via ethernet interface. In the MATLAB, due to the fairly stable delay between the transmission sequence and the receiving sequence, the start edge and stop edge of the receiving signal can be identified in the MATLAB with very small bias. Only the signal between the two edges are fed into the Fast Fourier Transform (FFT) operation to get the frequency spectrum, as shown in Figure 8. Then, the energy of the recieved useful signal is calculated based on the rule of cognitive radio network, i.e, only the energy at the subcarriers allocated for the users are counted.

5) Repeat the above tests several times by changing the positon of the target. The target is always placed on the line which is vertical to the direction of the transmitting antenna and moved from one side to the other side with pivot right face to the transmitting antenna. The receiving energy is calculated for each time of test. The receiving energy calculated in MATLAB is sensitive to
the position of the target, as shown in the Figure 9. This result is consistent with the result of the first stage of the experiment from the energy perspective. Position 1 to 6 are on the same line vertical to the direction of Tx antenna, while position 3 is right on the direction of TX radio wave. Test 7 is the case when the target is removed from the testing environment. The result shows that the receiving energy reaches the maximum only when the position of the target is right on the direction of the TX antenna. It should be noted that in all the tests, the target should be placed behind the trees to ensure the effect of the radio scattering caused by the trees. Actually, if the target is exposed outside the cover of the trees, because the radio scattering effect caused by the trees is removed, the receiving energy from the strong reflectivity by the metal plate will exceed the maximum value in the previous tests.

V. CONCLUSION AND FUTURE WORK

This paper presents the vision and challenge for the convergence of the wireless sensor network to cognitive radio network. The goal of the conceptual design is utilize the key features of the cognitive radio network as possible as it can, like the efficient spectrum utilization, software defined radio, etc. Although the experiment is based on the single transmitter and receiver, it still unveils the big potential of large scale wireless sensor network based on the cognitive radio network. The signal used for detection has non-contiguous spectrum as allocated to the secondary user. The receiving energy calculated based on such spectrum has visible relationship with the target position, i.e., the amplitude based detection and localization is practical when deploying the wireless sensor network.

The future experiment architecture of wireless sensor network is presented in Figure 10. Some works need to be exploited more.

1) Waveform design for the target detection. In the experiment of this paper, multi-frequency signal is used instead of real OFDM signal. In future, the real OFDM signal needs to be implemented to find more issues if real cognitive radio network is used as wireless sensor network.

2) Algorithms not only based on the amplitude are to be investigated, and also the theories like optimization and machine learning can be introduced to improve the capability or performance of the target sensing.

3) The collaboration and synchronization for the data collection at different nodes have some impact on the carrying out the network experiment.

4) The stronger computation engine, like the cloud computing, parallel computing can be integrated into the wireless sensor network to handle large complexity computing.

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